# Probing Sea Quark Polarization Using $W^{\pm}$ Production at PHENIX

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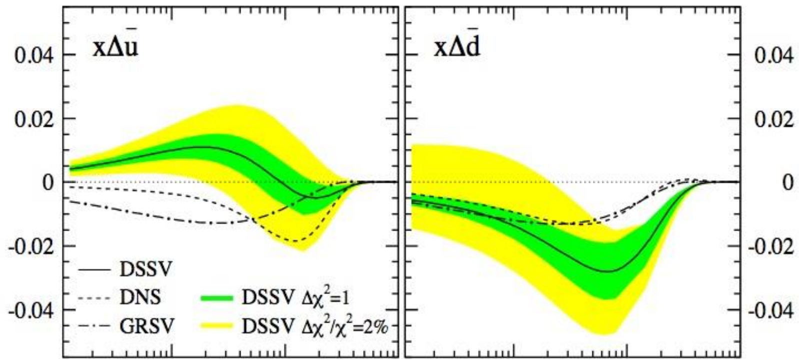
# Outline

- Motivation
- Mid-rapidity $W \rightarrow e$ Analysis
- Forward/backward rapidity $W \rightarrow \mu$ Analysis
- Summary

# Motivation

- Flavor-separated quark and anti-quark polarized PDF measurement

de Florian et al., PRL 101, 072001 (2008)



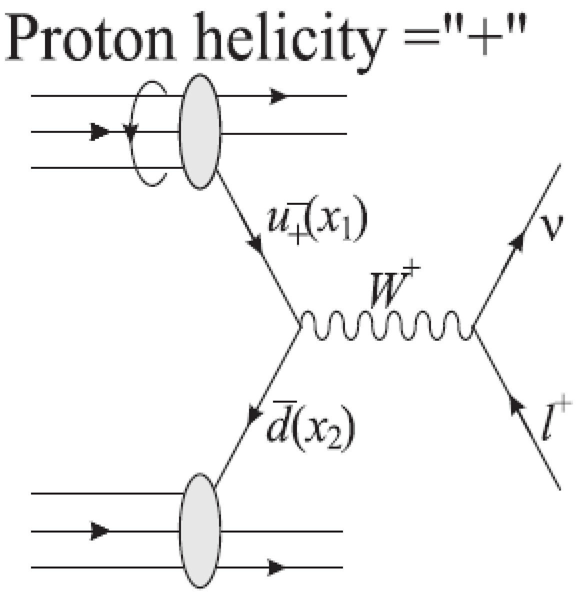

- Polarized SIDIS measurements (SMC, HERMES, COMPASS) sensitive to flavor separated quark anti-quark spin contributions
  - limited by large uncertainties of fragmentation functions
- Current estimates => $\bar{u}(x) \neq \bar{d}(x)$
  - $\Delta\bar{u}(x) \neq \Delta\bar{d}(x)$ ? (Pauli-blocking)

At RHIC, (anti)quark polarizations measured using maximal parity violation in $W$ production

- no fragmentation involved
- higher scale $Q^2$ set by $W$ mass
- extract $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$

$$W^{\pm} \rightarrow l^{\pm} + \nu$$

# $W$ Production in Polarized $p + p$




Bunce et al., Ann. Rev. Nucl. Part. Sci. 50:525 (2000)

- $W$ couples to only left-handed quarks and right-handed anti-quarks
- Longitudinal single spin asymmetry

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta \bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

(superposition of different W production criteria)

Flipping the spin orientation of one of the colliding protons and averaging over the other:

$$A_L = \frac{1}{P} \times \frac{N^+(e) - N^-(e)}{N^+(e) + N^-(e)}$$

where,

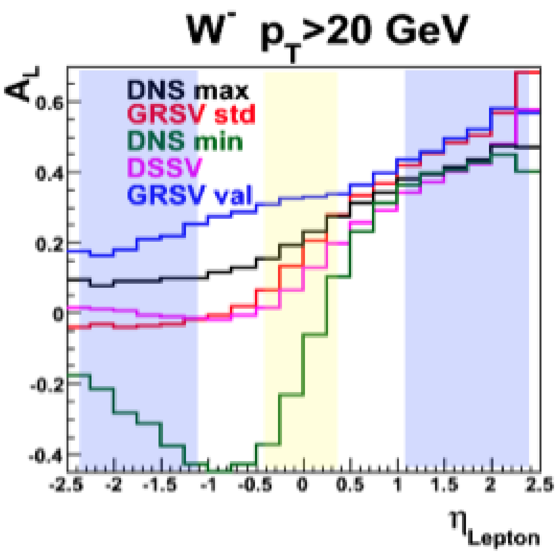
- N is electron yield normalized by luminosity
- P is luminosity weighted polarization

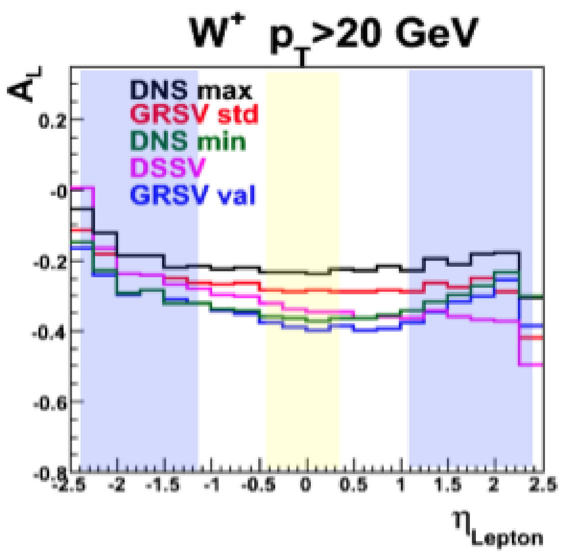
# Sensitivity to Quark Polarizations

$$\langle x_1 \rangle >> \langle x_2 \rangle : \quad A_L^{W^-} \approx \frac{\Delta d}{d}$$ (forward rapidity)

$$\langle x_1 \rangle << \langle x_2 \rangle : \quad A_L^{W^-} \approx \frac{\Delta \bar{u}}{\bar{u}}$$ (backward rapidity)

$W^{\pm} \rightarrow \mu^{\pm}$
**(forward/backward rapidities)**



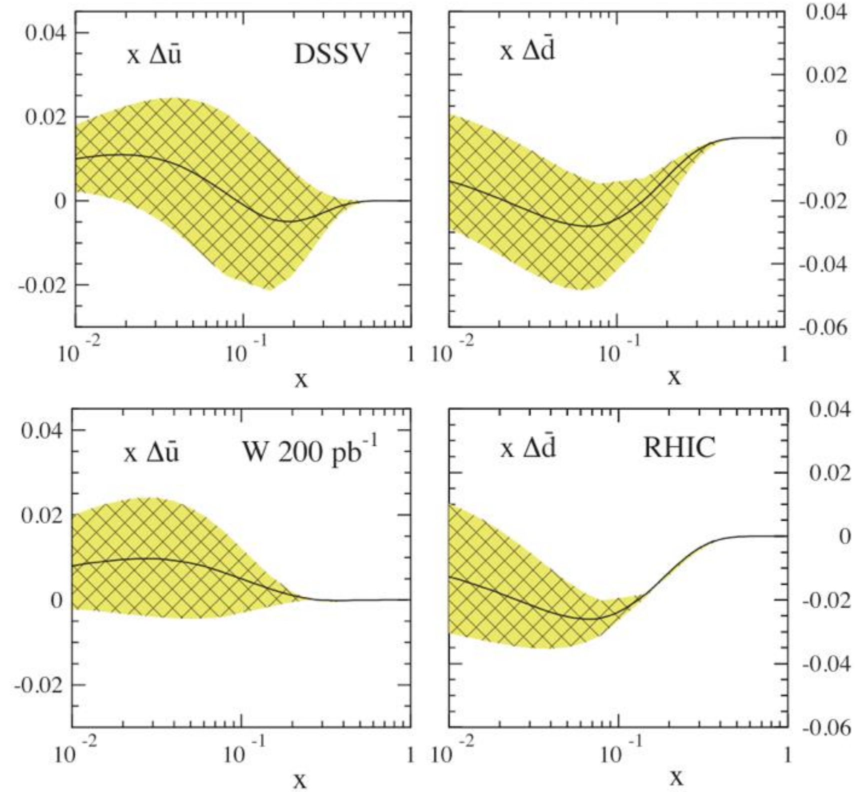

$W^{\pm} \rightarrow e^{\pm}$
**(mid-rapidity)**
measuring the mixture of quark flavor contribution:

- For $W^{+}$, combination of $\Delta u$ and $\Delta \bar{d}$
- For $W^{-}$, combination of $\Delta \bar{u}$ and $\Delta d$

# Impact on Sea-quark polarizations

Phys. Rev. D 81, 094020 (2010)

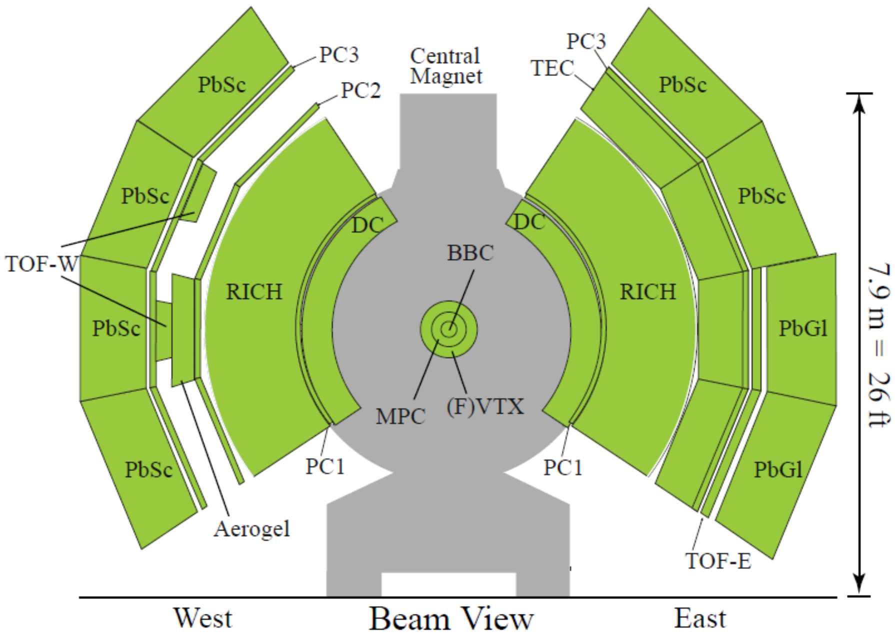
DSSV global analysis




DSSV global analysis
**+** simulated 200 $pb^{-1}$
W $A_L$ at proton-proton collisions in RHIC

Significant impact on uncertainties

# Mid-rapidity $W^{\pm} \rightarrow e^{\pm}$ Analysis




## Central arm (|η|<0.35)

- 2 arms: Δϕ = π/2 *2
- Electromagnetic Calorimeter (PbSc,PbGl)
  ΔφxΔη~0.01x0.01
- Drift (and Pad) Chambers for tracking and charge separation
- VTX detector

## Strategy

Looking for high energy $e^{\pm}$

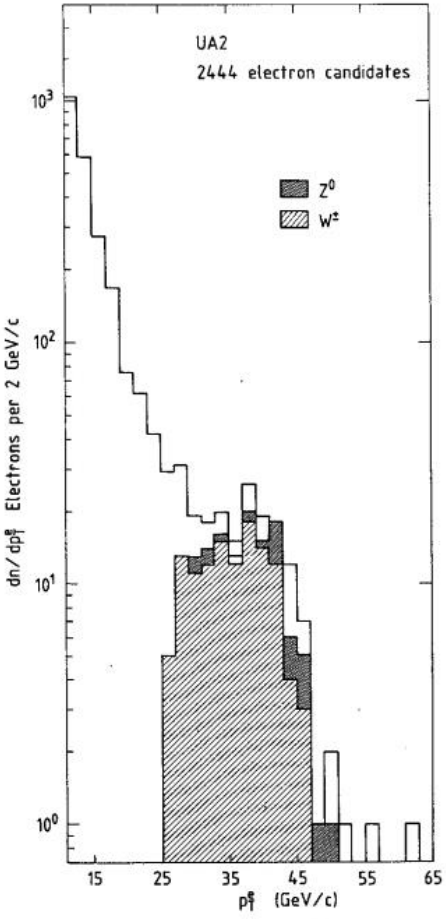
- Online trigger based on EMC 4x4 tower sum
  - fully efficient at $p_T$>10 GeV
- High energy EMC clusters matched to DC tracks
  - (Δϕ < 0.02 rad)

## Basic cuts

- Vertex cut: |z| < 30 cm
- Removal of tracks with DC |α|<1 mrad
  - α – bending angle
- Time of Flight cut
  - reduces cosmic background

# Identifying Signal

- Detector is non-hermetic
- Cannot identify W's on event by event basis
- Need to form the pT spectra for decaying $e^{\pm}$
- Clear jacobian peak at ~40 GeV
  - corresponds to signal
- Looking for excess of events over background in the signal region (30-50 GeV)



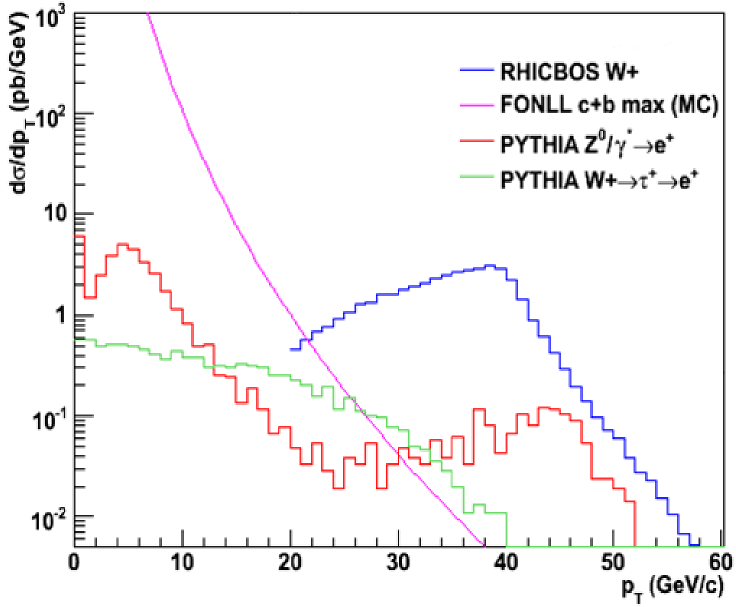
# Background Processes

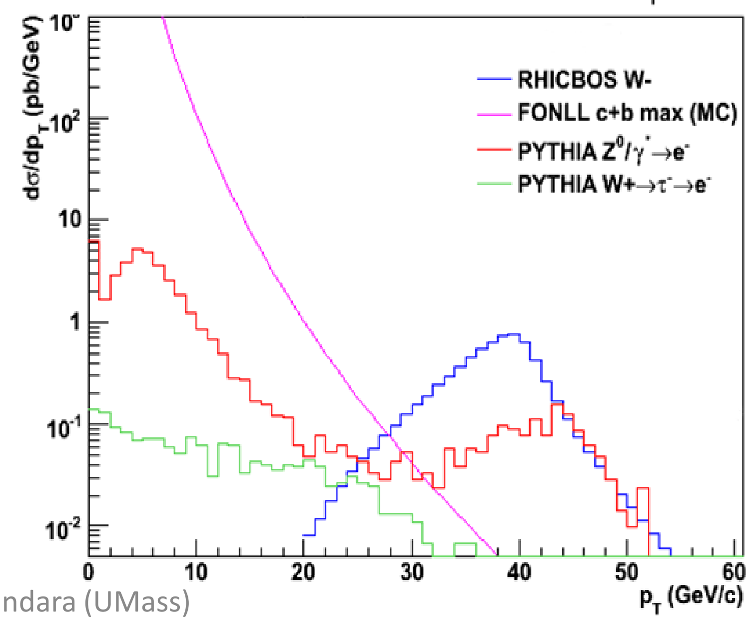
**Irreducible background:-**

- $Z \rightarrow e^{+} + e^{-}$ (part of signal)
- Heavy quark decay: $c, b \rightarrow e^{\pm} + X$
- $W \rightarrow \tau + \nu_{\tau} \rightarrow e\, \nu_{e}\, \nu_{\tau}\, \bar{\nu_{\tau}}$

**Reducible background:-**

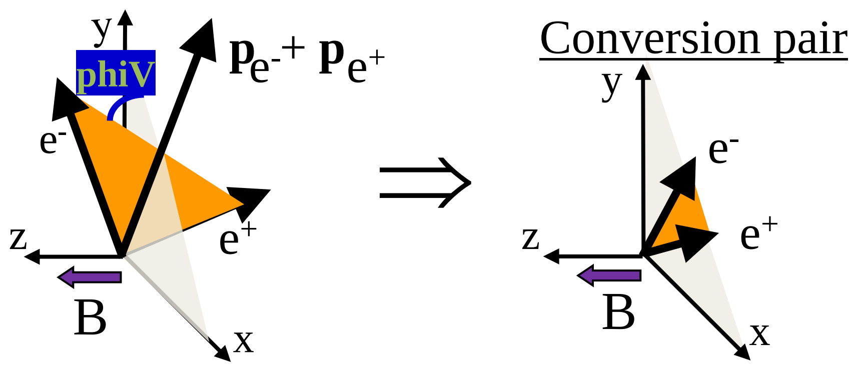
- Charged hadrons
- $\pi^{0} \rightarrow \gamma \rightarrow e^{+}e^{-}$ before DC
  - VTX increases photon conversions (thickness ~14% $X_0$)
- Cosmic background
- Accidental track match



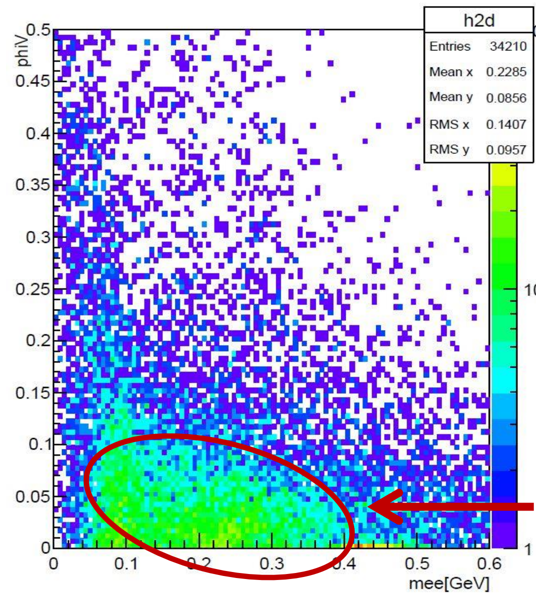



# VTX Conversions

**phiV** is the angle plane of pair makes with plane normal to beam direction




## VTX conversions

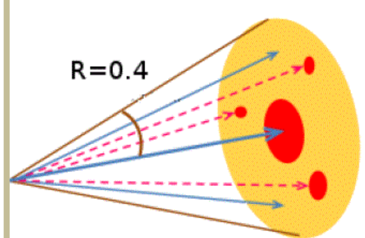



$\pi^0$ simulations

conversions in VTX barrels and electronic support

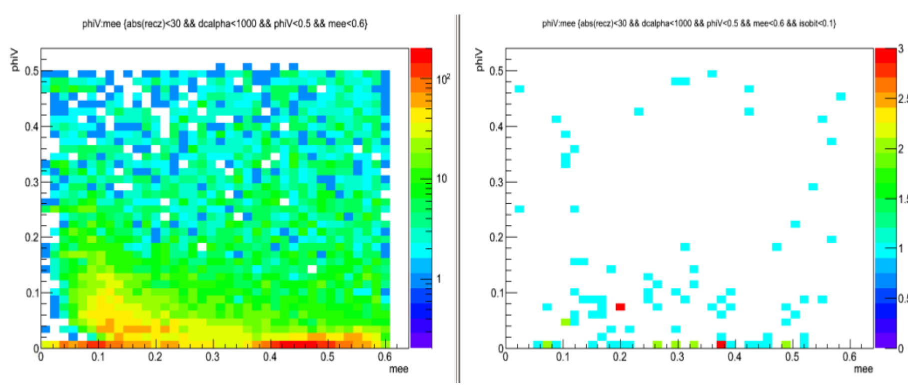
## Isolation cut

rel. isolation cut = $\frac{(E_{tot}-E_{candidate})+p_{DC}}{E_{candidate}}$ in a cone of R=0.4 **< 10%**

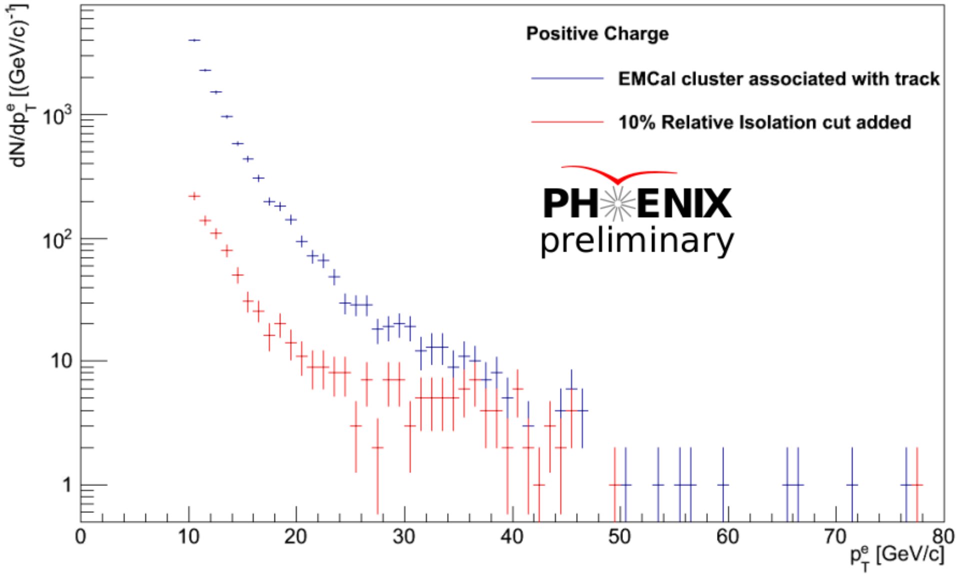


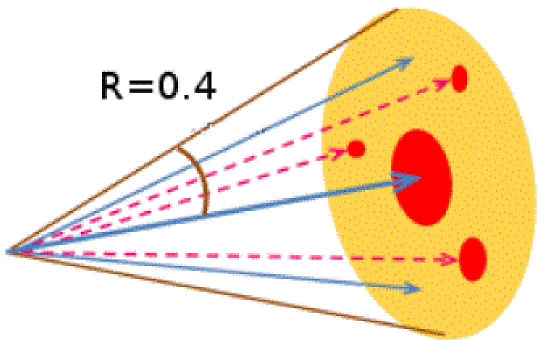

Before isolation cut

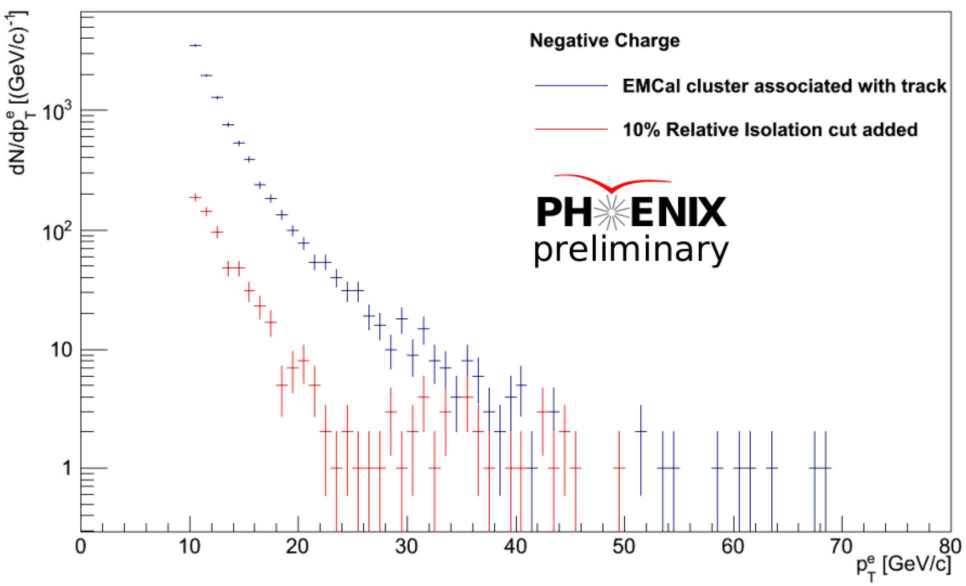
After isolation cut



# Isolation Cut

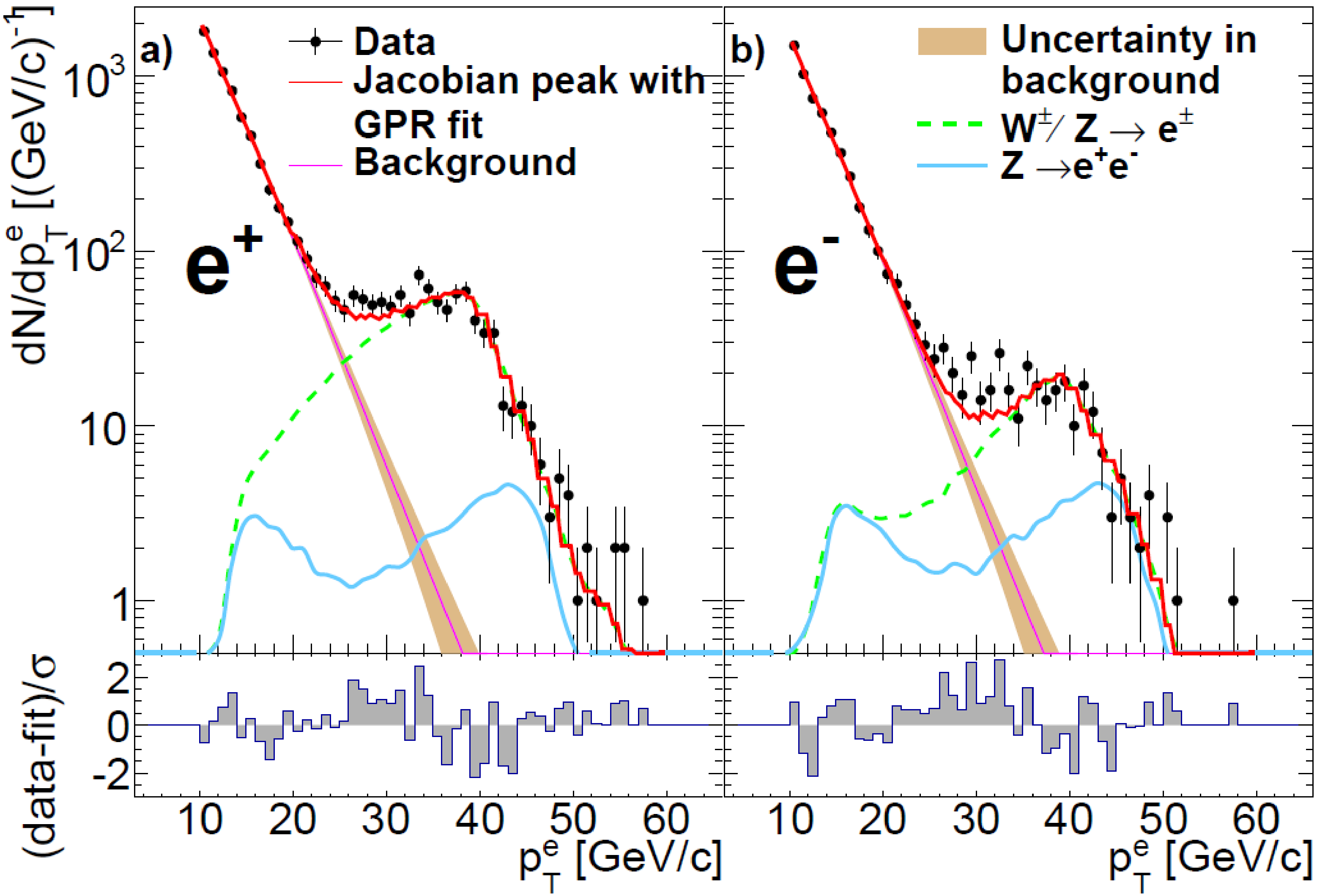



The relative isolation cut removes more than a factor of 10 in the background dominated region (10-20 GeV) while leaving the signal region (30-50 GeV) relatively untouched

# Run 13 $W^{\pm}$ Spectra




Latest results [arXiv:1504.07451]()

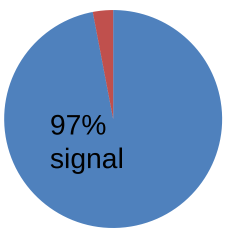
# Run 13 $W^{\pm}$ Spectra

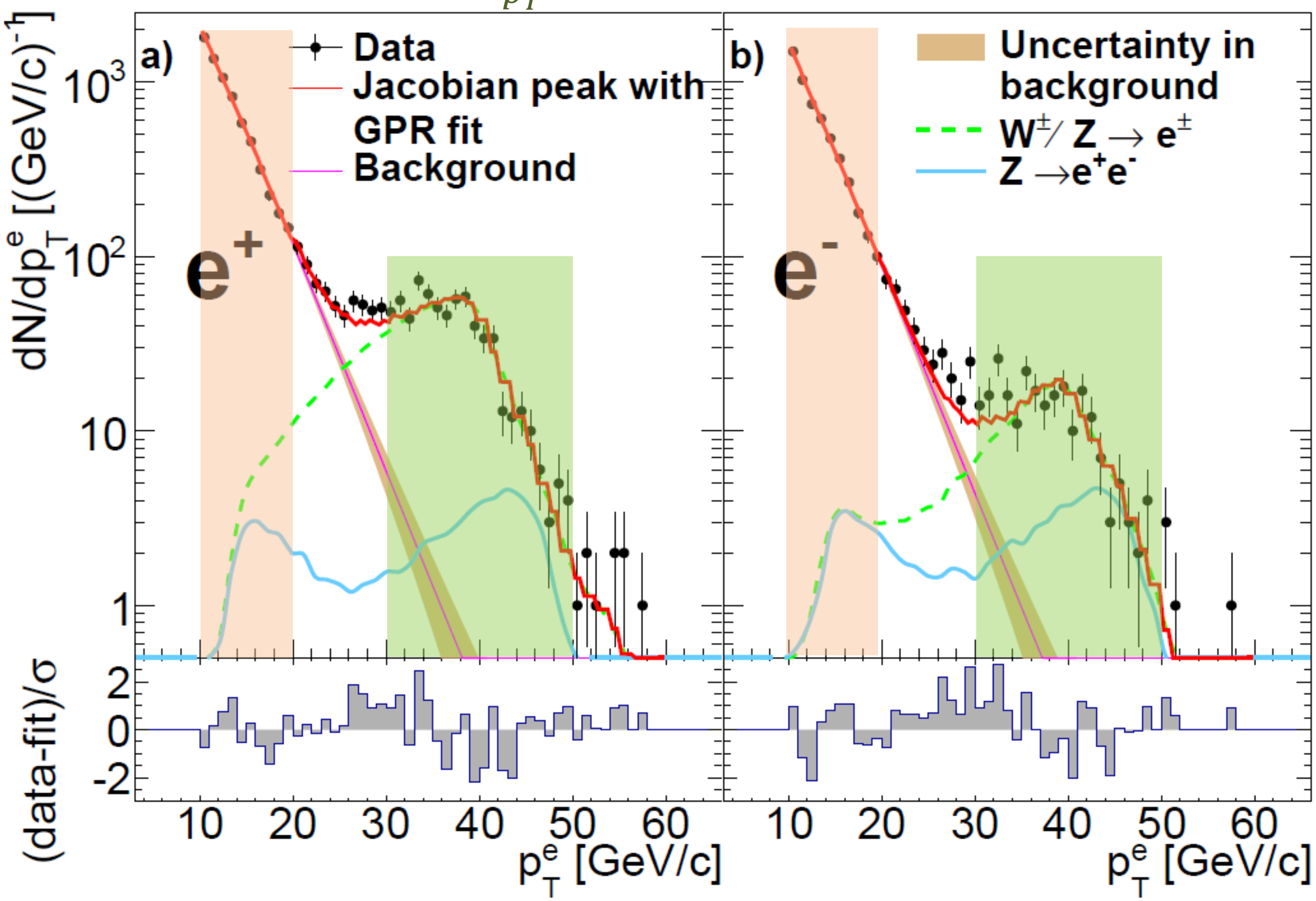
Signal region: $30 < p_T < 50$ GeV  Background region: $10 < p_T < 20$ GeV

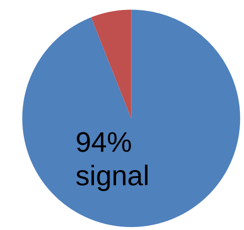
Background estimation using two independent methods:

- Gaussian Processes for Regression (GPR)
- Modified power law $\{f(p_T) = \frac{1}{p_T{}^{[0]+[1]*\log(p_T)}}\}$

fit simultaneously with simulated jacobian peak shape

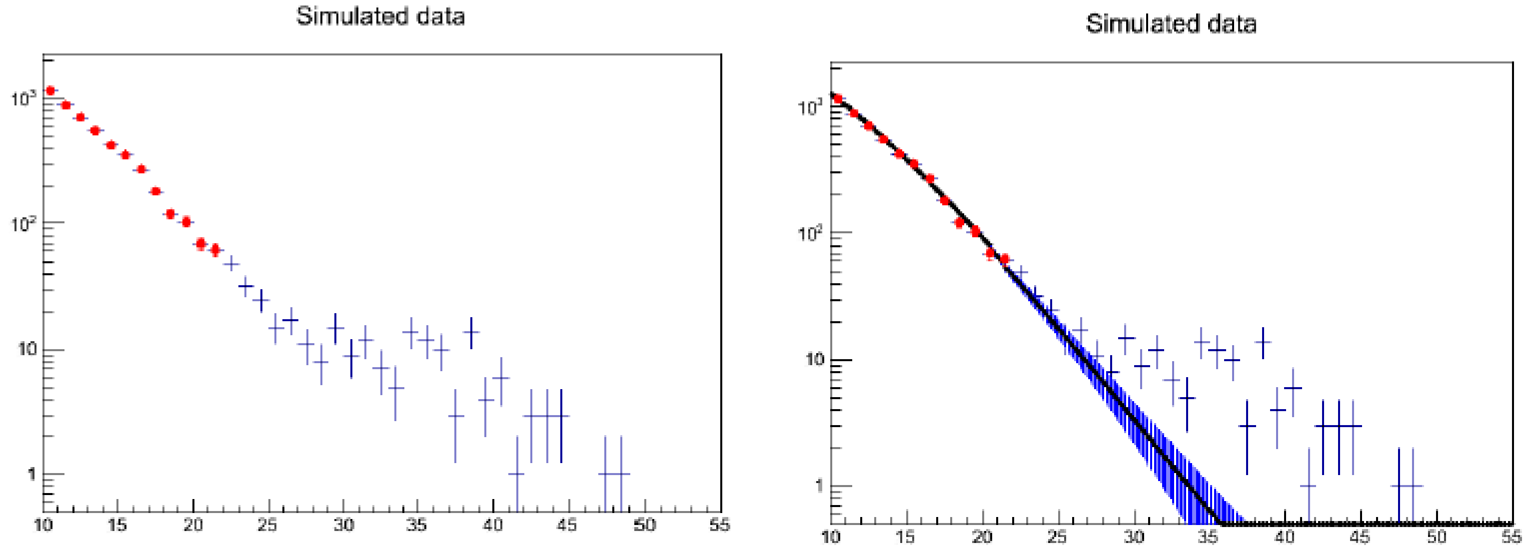


# Background Estimation

## Using Gaussian Processes for Regression (GPR)



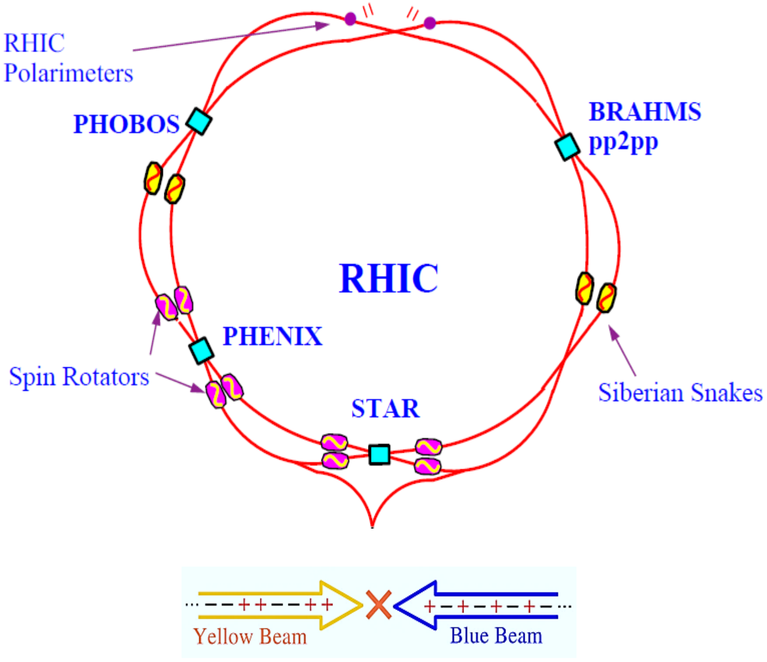

- Use background controlled region to get a shape and extrapolate to the signal region.
- GPR gives the background contribution and its uncertainty.
- The results have been cross checked using a classic functional form (modified power law).
  - good agreement
  - any differences are included in systematic errors.

# Asymmetry Calculation

$$A_L = \frac{1}{P} \times \frac{N^+(e) - N^-(e)}{N^+(e) + N^-(e)}$$

where,
- N is electron yield
- P is luminosity weighted polarization

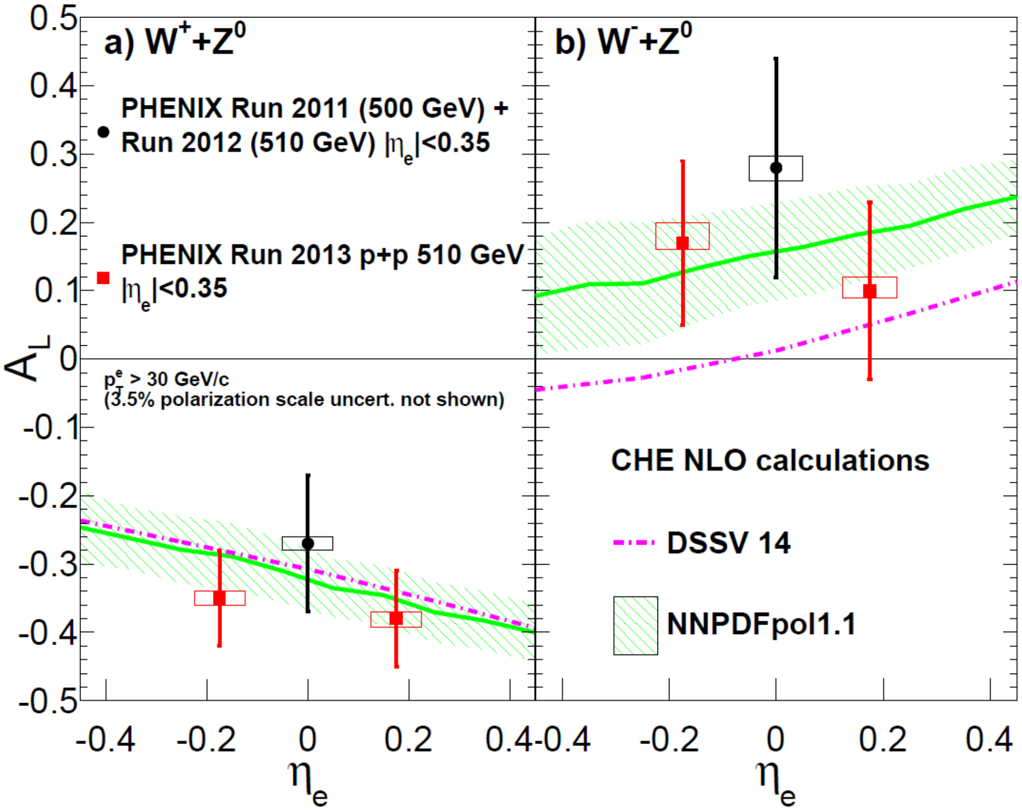
- At RHIC, two beams in opposite directions, 120 bunches in each ring, with helicity of pairs alternating.
- Calculate asymmetry taking BLUE beam as polarized, averaging over YELLOW beam.
- Repeat by taking YELLOW beam as polarized, averaging over BLUE beam.
- Combine results (weighted averages).
- Asymmetry is also calculated using a likelihood method.
- Asymmetry result corrected for background through dilution factor.



# Single-Spin Asymmetry $A_L$

| Year | √s (GeV) | ∫Ldt (pb$^{-1}$) | Pol. (%) | P$^2$L (pb$^{-1}$) |
|---|---|---|---|---|
| 2011 | 500 | 19.8 | 51 | 5.1 |
| 2012 | 510 | 34.7 | 56 | 10.9 |
| 2013 | 510 | 184.0 | 55 | 55.6 |

arXiv:1504.07451




- Run 2011, 2012 and 2013 results have been finalized.
- 27 times more statistics compared to 2009 PHENIX data.
- Submitted for publication **arXiv:1504.07451**
- Good agreement with the NNPDFpol1.1 set

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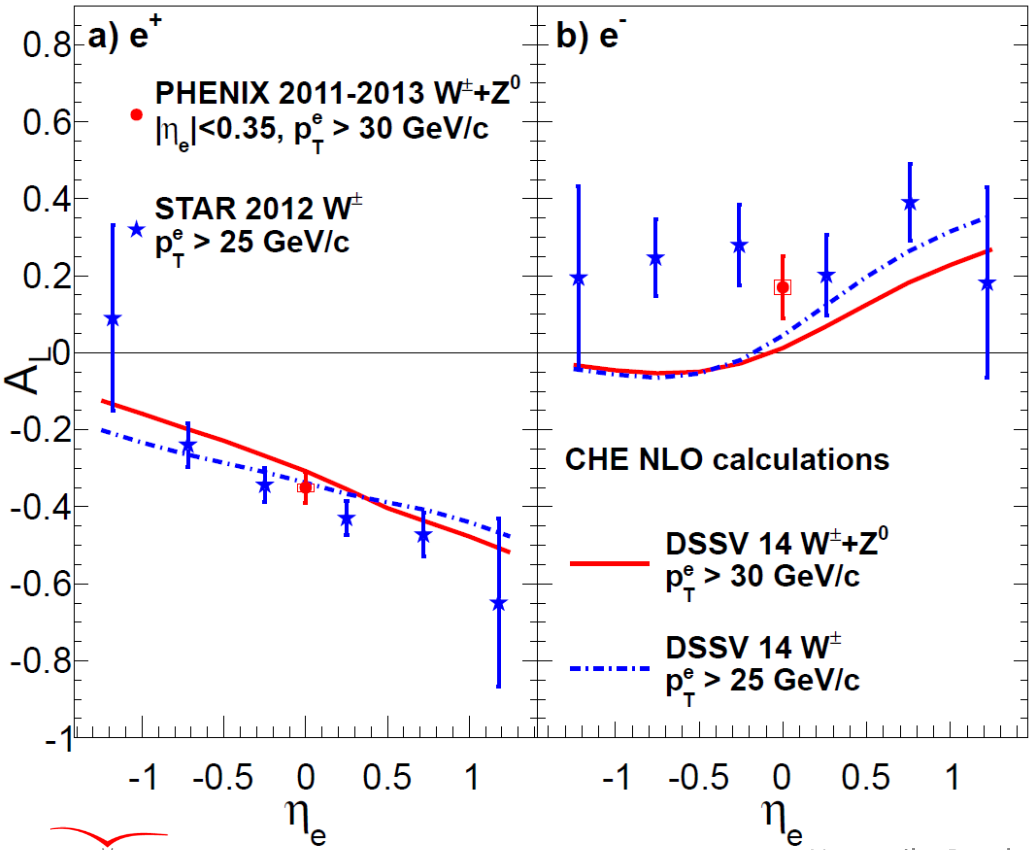


- Comparison with STAR results.
- Both data sets show the same trend with respect to the DSSV central values.
- Show preference to a larger $\Delta\bar{u}$ contribution.

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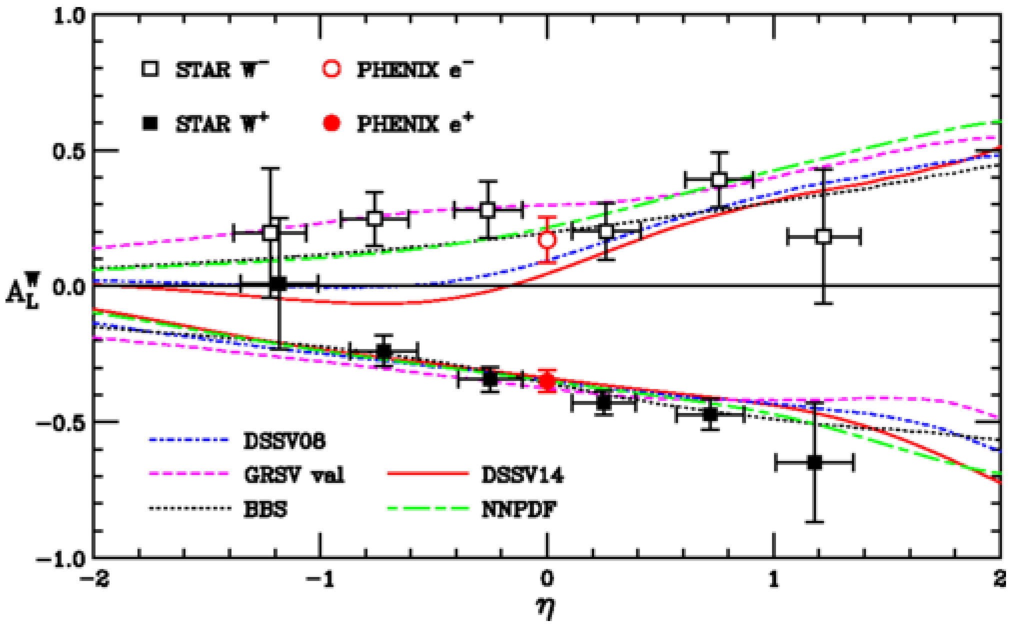
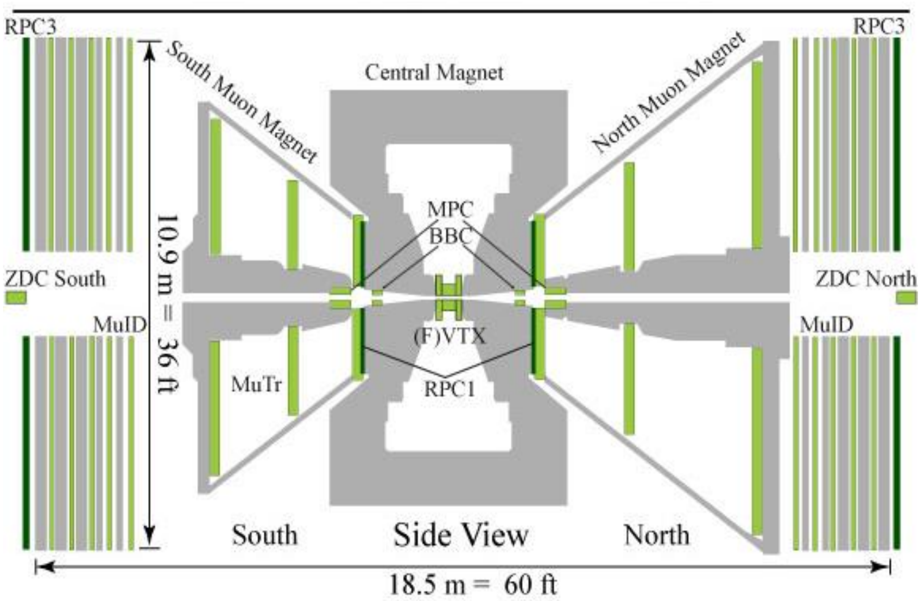
PhysRevD.91.094033




- Comparison with STAR results.
- Both data sets show the same trend with respect to the DSSV central values.
- Show preference to a larger $\Delta\bar{u}$ contribution.
- Featured in the latest theory calculation
  - overall agreement with the available predictions.

# Forward $W^{\pm} \rightarrow \mu^{\pm}$ Analysis

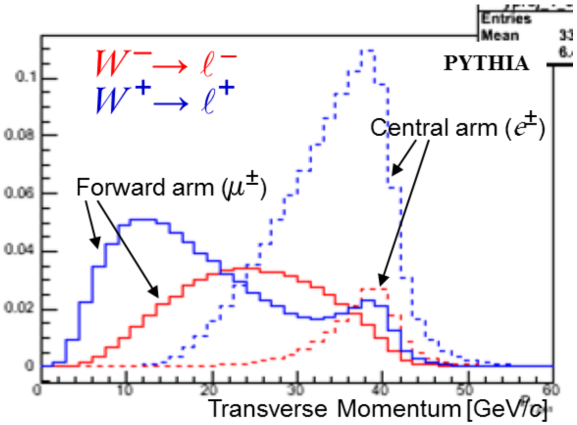



**Muon arms**

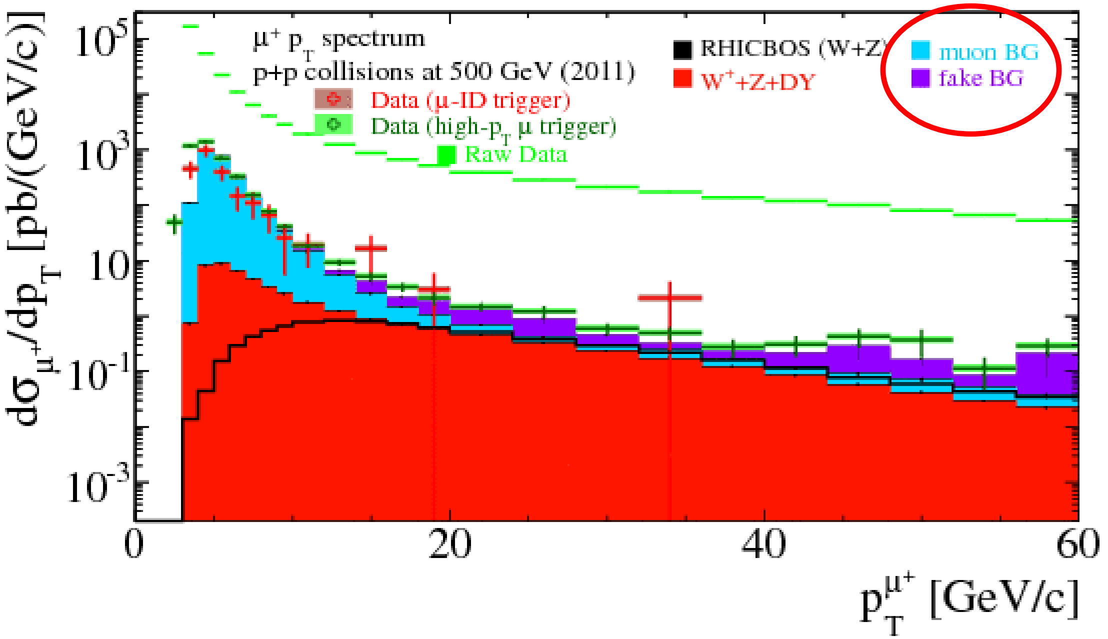
- 1.2<η<2.4 (North), -2.2<η<1.2 (South)
  Δϕ = 2π
- Muon Tracker (MuTr)
  - tracking, momentum measurement
- Muon Identifier (MuID)
  - particle ID

- Resistive Plate Chamber (RPC)
  - timing improvement, background rejection
- Forward Vertex Detector (FVTX)
  - high resolution tracking
- Fully upgraded in 2012
  - trigger to reject low momentum muons

# Background Processes




No jacobean peak to distinguish signal from background

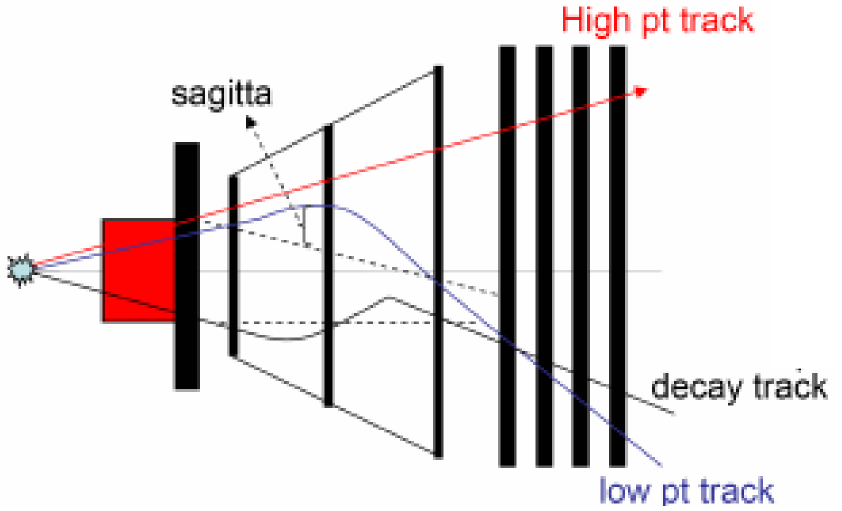



- **Hadronic BG:**

Low energetic hadrons decay within MuTr, misreconstructed as high pT track =>"fake muons"

- **Muon BG:**

From heavy flavor, quarkonia, Drell-Yan; get smeared to high pT

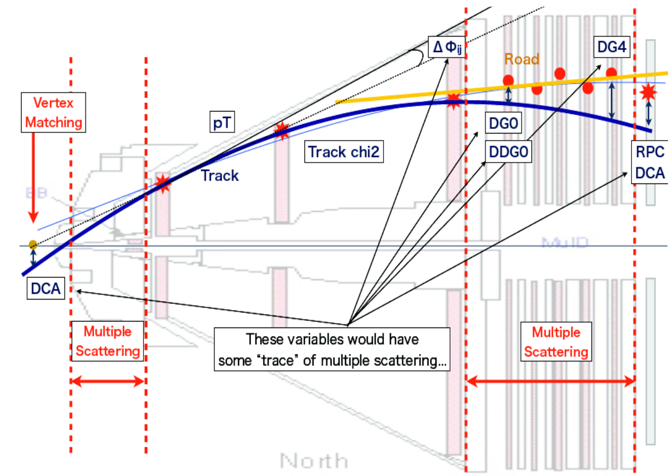


# Analysis Strategy

**Multivariate cut for pre-selection:**

- Determine likelihood “λ” of an event to be signal or background

$$\lambda = p(DG0, DDG0)p(chi2)p(DCA_r)p(Rpc1/3dca)p(dr_{fvtx} * d\theta_{fvtx})p(d\phi_{fvtx})$$

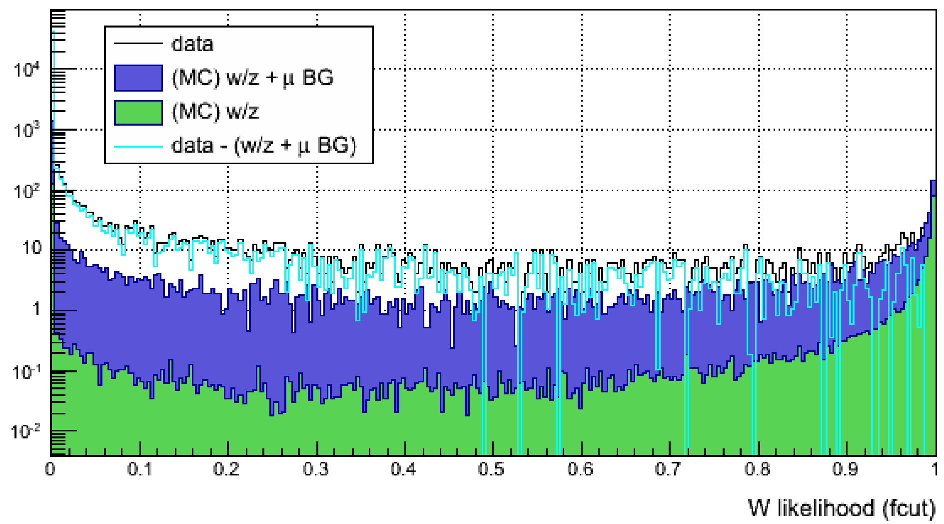



- Calculate “Wness” defined as

$$Wness = \frac{\lambda_{sig}}{\lambda_{sig}+\lambda_{bkg}}$$

$\lambda_{sig}$ - from Pythia+PISA MC simulation
$\lambda_{bkg}$ - from data

- Events with Wness > 0.92 are selected



# Background Estimation

**Unbinned maximum likelihood fit**

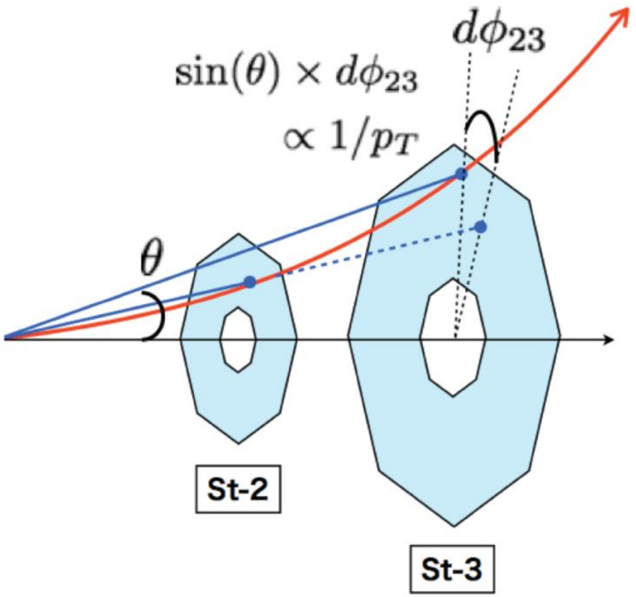
- Signal and background fractions calculated minimizing likelihood function

$$L(\theta \mid X) \equiv \frac{n^N e^{-n}}{N!} \prod_{x_i \in X}^{N} \left[ \sum_c \frac{n_c}{n} p_c(x_i) \right], \qquad n = \sum_c n_c$$

$p_c(x_i)$ – probability distribution functions from simulation (W signal, muon BGs) and data (hadron BGs) using η, dw23

$$x_i = (\eta_i, \mathrm{dw}_{23_i}) \qquad \theta = (n_{sig}, n_\mu, n_{had})$$

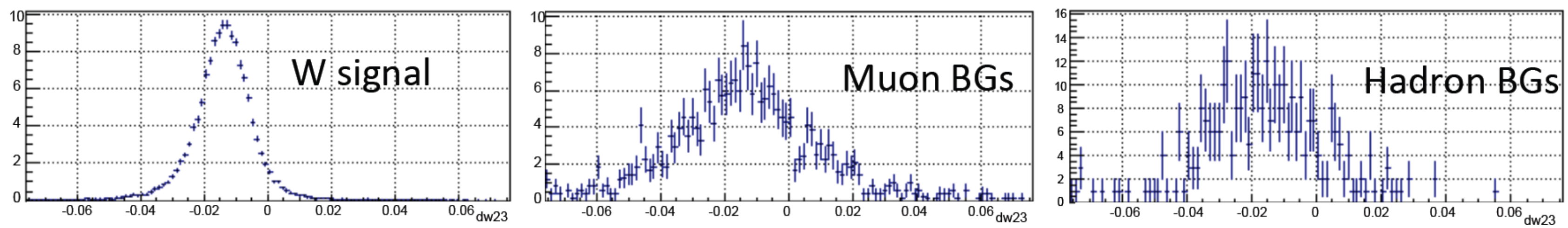
- Hadronic BG dominates at low Wness
  - extrapolate dw23 to Wness > 0.92



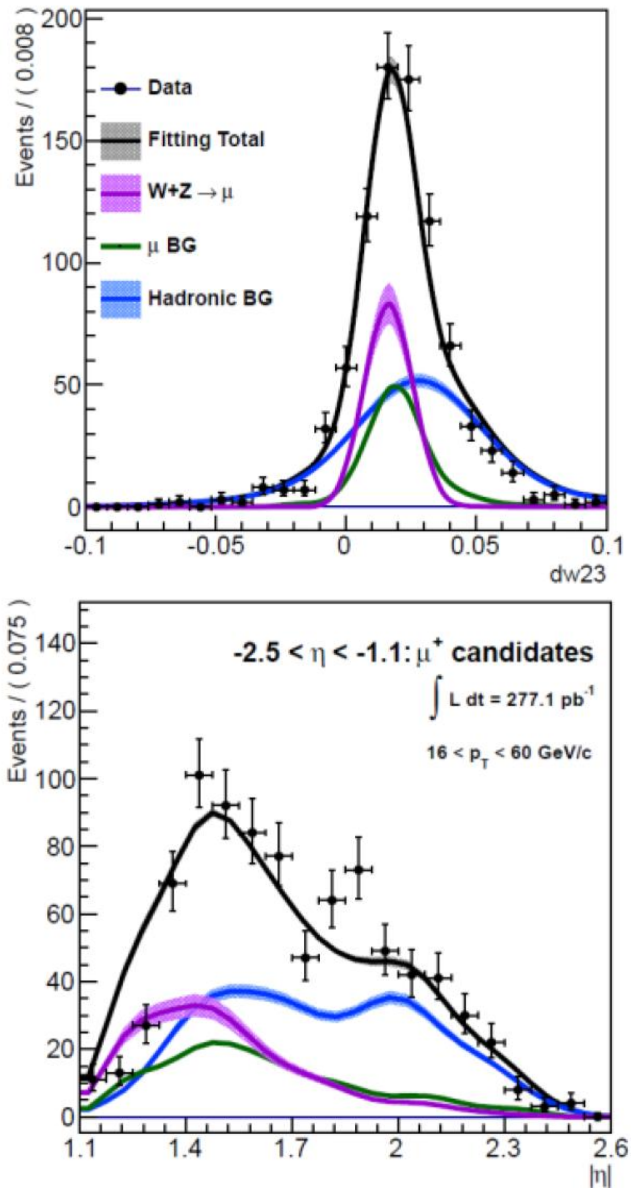

$$\mathrm{dw}23 \equiv p_T \times \sin(\theta) \times d\phi_{23}$$

(reduced azimuthal bending)

dw23 distributions (16 < $p_T$ < 60 GeV/c, f > 0.02)



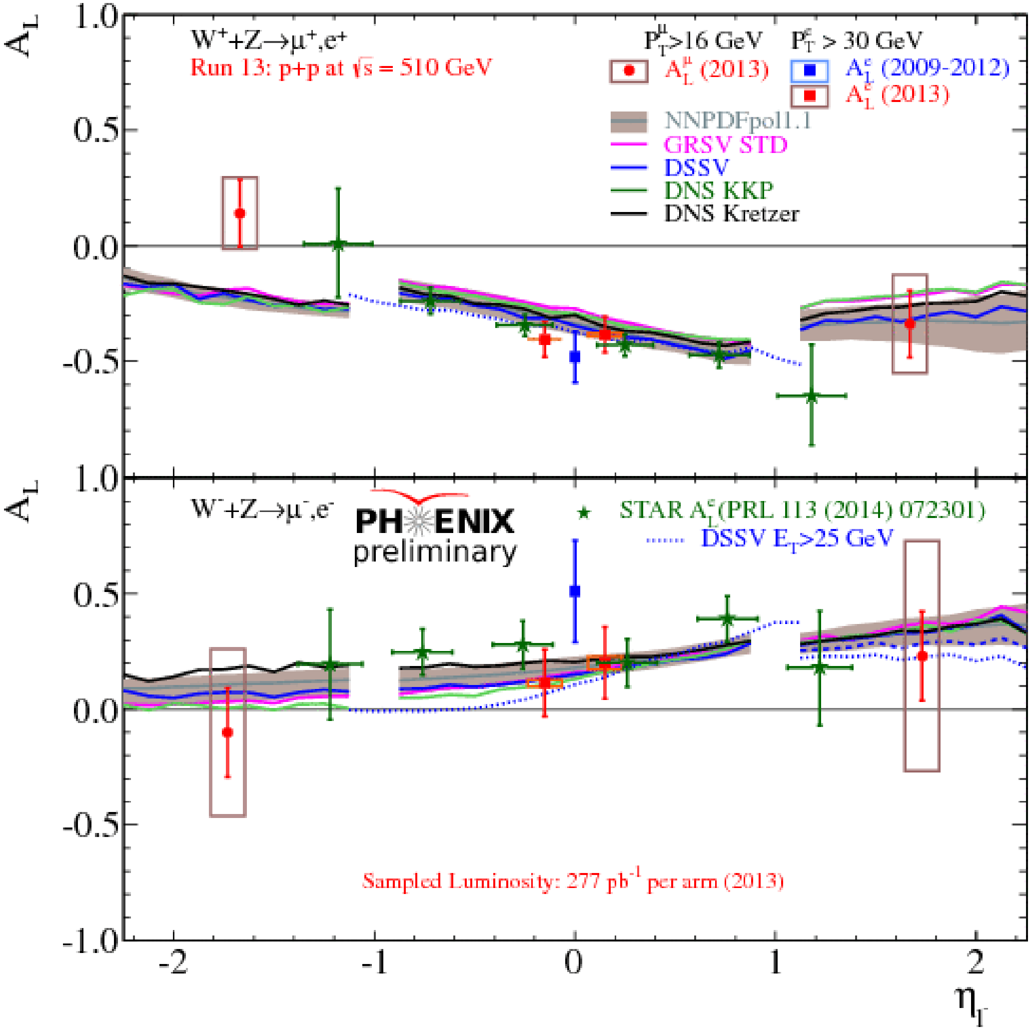
# Signal / Background Ratio




1D projections of 2D unbinned maximum likelihood fit

- $16 < p_T < 60$ GeV/c, $f > 0.92$
- Use η and dw23 fits to count and calculate S/B
- S/B ratio used as a dilution factor to calculate the corrected asymmetry.

# Forward Asymmetry Results



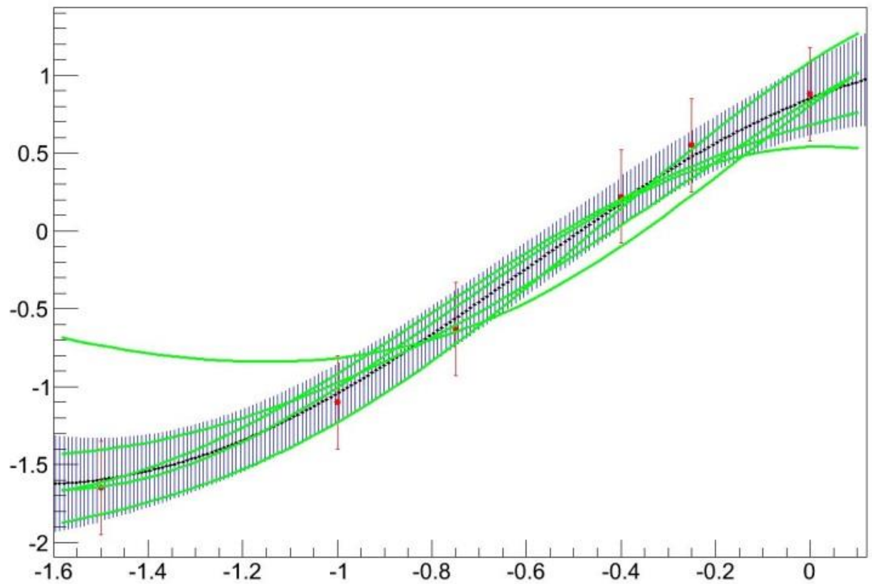

- Run 2013 preliminary results.
- Results are in agreement with theoretical predictions within uncertainties.
- Currently working to improve the systematic uncertainties.
- Moving towards the final result and publication.

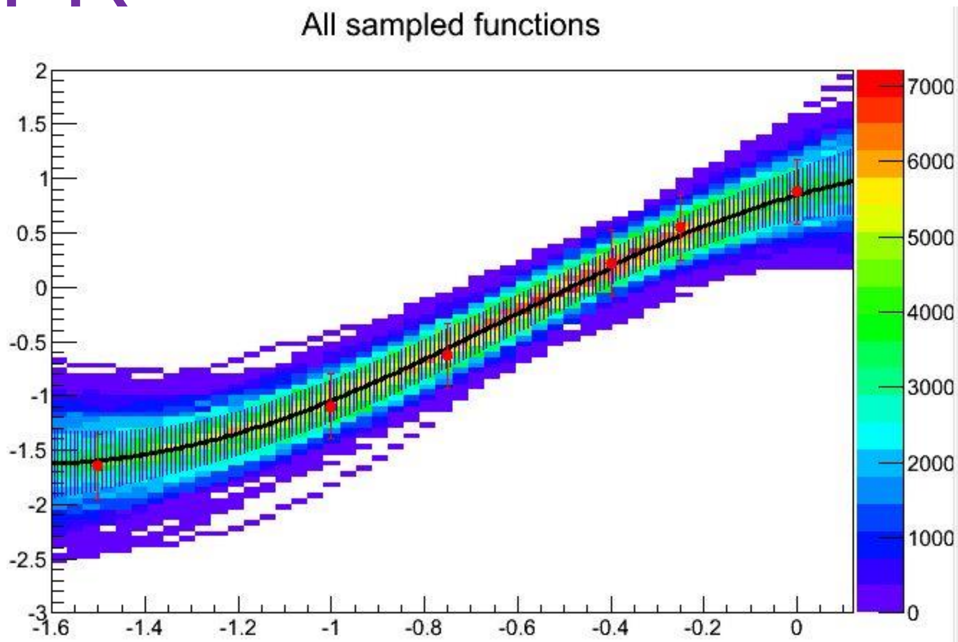
# Summary

- Run 2013 :-
  - PHENIX recorded more than two times the statistics from Run 2011 and 2012 combined
  - Single spin asymmetries $A_L$ have been measured are consistent with DSSV global analysis.
    - $W \rightarrow e$ results favoring larger $\Delta\bar{u}$ contribution.
  - $W \rightarrow e$ results have been submitted for publication along with 2011 and 2012 data.
  - $W \rightarrow \mu$ preliminary results have been presented.
  - Improved precision will reduce uncertainties on $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$

- With Run 2013 and previous results, RHIC $W$ program is expected to improve our knowledge on polarized sea quark distributions.

# GPR




- Through the use of a covariance function determined from the data the GPR can make predictions for data sufficiently close to the input set.
- It samples over a whole class of functional forms and returns predictions that are consistent with the data.
  - The class is determined by the covariance function
- Sampling over these functions and filling a 2D histogram will give a Gaussian distribution for each prediction point
- The mean of the Gaussian distribution is the prediction and the sigma is the uncertainty